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River Incision in Relation to Post-Glacial Events in the Humber River Basin, Ontario
Incision des cours d'eau par les événements post-glaciaires dans le bassin de la rivière Humber, Ontario

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Résumé de l'article

La morphologie des vallées dans le bassin de la rivière Humber découle essentiellement des processus ayant agi durant les derniers 13 000 ^{14}C BP. Certains segments de vallées présentent des caractéristiques uniques, particulièrement en ce qui a trait à la morphologie en plan : les boucles et les méandres. Dans cette étude, l'évolution des vallées du bassin de la rivière Humber au cours de l'Holocène et à la fin du Wisconsinien est étudiée de façon à déterminer les changements morphologiques et leur évolution vers leur forme actuelle. Des datations au ^{14}C et des modèles d'élévation de terrain indiquent que la majeure partie de l'incision des vallées s'est produite durant ou peu après la déglaciation régionale. Les composantes des méandres de vallées et les patrons des terrasses fluviatiles indiquent que la morphologie actuelle des vallées est attribuable à des rivières ancestrales plus larges. Outre le rôle attendu des apports en eau de fonte associés à la déglaciation soient attendues, il est probable que les effets climatiques et hydrogéologiques des changements du niveau d'eau des lacs proglaciaires aient aussi joué un rôle dans l'évolution des vallées du bassin de la rivière Humber.

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RIVER INCISION IN RELATION TO POST-GLACIAL EVENTS IN THE HUMBER RIVER BASIN, ONTARIO

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ABSTRACT River valleys in the Humber River drainage basin have derived most of their morphology from processes occurring over the last 13 000 ^{14}C BP. Some of the valley reaches possess very distinct characteristics in terms of plan-view morphology, such as valley meandering and loop features along the valley sides. In this study, the valley morphology and stratigraphy of the upper Humber River basin are examined in order to assess the character of post-glacial valley evolution. Existing knowledge of late Wisconsinan and Holocene events has been considered to place this valley evolution into a regional context. Radiocarbon dating and digital elevation models suggest that the majority of valley incision occurred during or soon after regional deglaciation. Looping valley features and terrace patterns indicate that most valley morphology can be attributed to larger ancestral rivers. Although direct melt-water contributions are expected due to deglaciation, it is suggested that other processes due to the climatic and hydrogeologic effects of fluctuating proglacial lake levels also played a role.

RÉSUMÉ *Incision des cours d'eau par les événements post-glaciaires dans le bassin de la rivière Humber, Ontario.* La morphologie des vallées dans le bassin de la rivière Humber découle essentiellement des processus ayant agi durant les derniers 13 000 ^{14}C BP. Certains segments de vallées présentent des caractéristiques uniques, particulièrement en ce qui a trait à la morphologie en plan : les boucles et les méandres. Dans cette étude, l'évolution des vallées du bassin de la rivière Humber au cours de l'Holocène et à la fin du Wisconsinien est étudiée de façon à déterminer les changements morphologiques et leur évolution vers leur forme actuelle. Des datations au ^{14}C et des modèles d'élévation de terrain indiquent que la majeure partie de l'incision des vallées s'est produite durant ou peu après la déglaciation régionale. Les composantes des méandres de vallées et les patrons des terrasses fluviatiles indiquent que la morphologie actuelle des vallées est attribuable à des rivières ancestrales plus larges. Outre le rôle attendu des apports en eau de fonte associés à la déglaciation soient attendues, il est probable que les effets climatiques et hydrogéologiques des changements du niveau d'eau des lacs proglaciaires aient aussi joué un rôle dans l'évolution des vallées du bassin de la rivière Humber.

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INTRODUCTION

Late Wisconsinan events in the area corresponding to the contemporary Humber River drainage basin played a significant role in landscape evolution and had long-lasting effects on valley morphology in the basin. In particular, topographic and sedimentary characteristics in the area of the Oak Ridges Moraine may have had a prominent influence on the fluvial activity of melt-water during deglaciation. Water at the melting edges of the Laurentide Ice Sheet tended to form large proglacial lakes, and their topographic confinement was accentuated by isostatic depression. However, the effects of these glacial lakes may not be completely understood simply by their extent and the location of their outlet. Initial fluvial processes occurring on deglaciated surfaces would have responded to the dynamic atmospheric and hydrogeologic conditions driven by such large amounts of ponded water.

As the Laurentide continental ice sheet retreated from southern Ontario, the action of ice lobes resulted in the formation of moraines and the impoundment of proglacial lakes. Evidence of these proglacial lakes is recorded not only in sediments, but also in many exposed shoreline bluffs throughout the Great Lakes region (Terasmae, 1980; Chapman and Putnam, 1984; Sly and Prior, 1984; Anderson and Lewis, 1985; Muller and Prest, 1985). Interpretation of deglacial and post-glacial events is complicated by shoreline identification and radiocarbon (^{14}C) dating techniques; however, the most significant challenge is associated with the patterns and rates of isostatic rebound. This makes correlation of basin and regional water levels difficult, as the only true reference point is the centre of the earth. Despite these uncertainties, regional post-glacial events would have implications for patterns of fluvial erosion and drainage over newly exposed basin surfaces. Late Wisconsinan deglaciation in the Lake Ontario basin is characterized by events such as the formation of the Oak Ridges Moraine and the impoundment of glacial Lake Iroquois (Fig. 1); however, these events are also associated with other deglaciation activities in Southern Ontario.

As the Oak Ridges Moraine was formed, deposition between these lobes left behind a complex stratigraphy of sediments, which may also have been influenced by melt-water ponding between the lobes and the Niagara Escarpment at the western edge (Duckworth, 1979; Chapman and Putnam, 1984; Chapman, 1985). Described as an interlobate moraine, the stratified moraine complex is thought to have formed over a number of stages, with a sequence from subglacial sedimentation, to subaqueous fan and delta sedimentation, to ice-marginal sedimentation (Chapman, 1985; Barnett *et al.* 1998). The resulting feature is a topographic high extending approximately 160 km east to west and acting as a drainage divide between present day Lake Ontario and drainage to the north (Barnett *et al.,* 1998).

Models of Lake Ontario post-glacial water levels (Fig. 2) have been proposed by Sly and Prior (1984) and Anderson

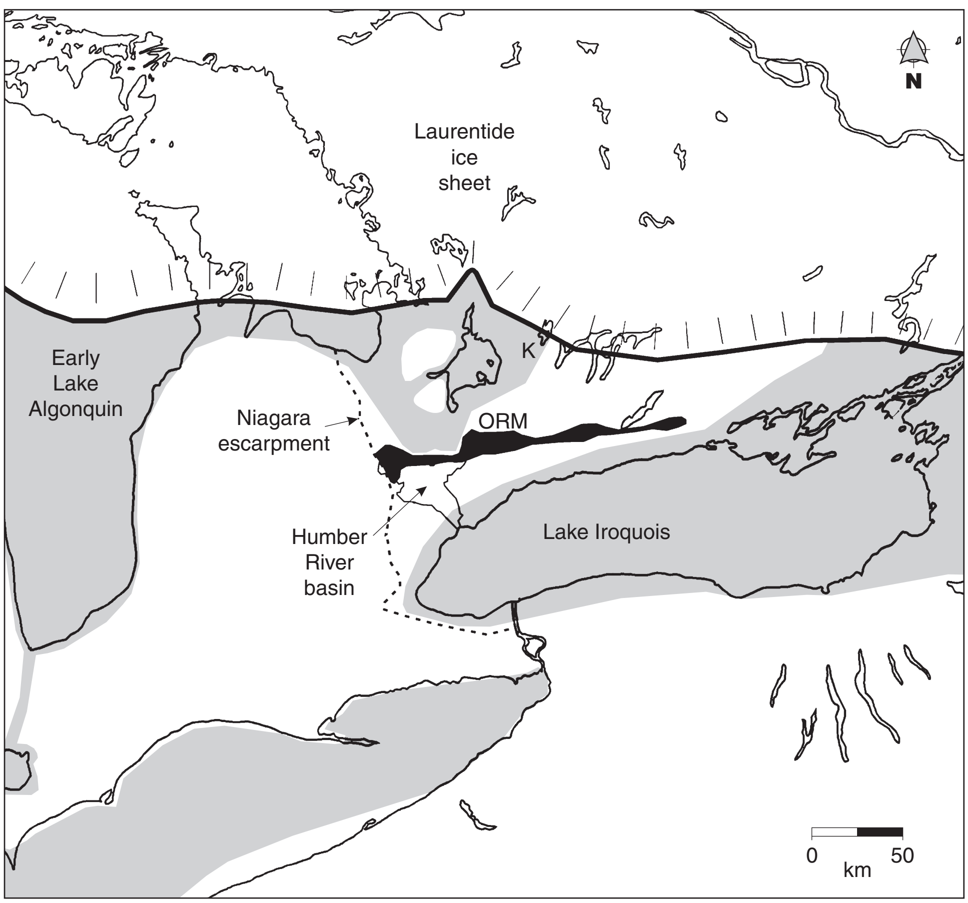

FIGURE 1. Location map of the Humber River basin relative to deglacial event approximately 12 000 ^{14}C BP. Adapted from Chapman and Putnam (1984) and Muller and Prest (1985). ORM: Oak Ridges Moraine, K: Approximate location of Lake Algonquin drainage at Kirkfield following further ice retreat.

Carte de localisation du bassin de la rivière Humber en relation avec certains événements reliés à la déglaciation de la région vers 12 000 ^{14}C BP. Adapté de Chapman et Putnam (1984) et Muller et Prest (1985). ORM : Moraine de Oak Ridges, K : Localisation approximative du drainage du lac Algonquin à Kirkfield en fonction du retrait subséquent des glaces.

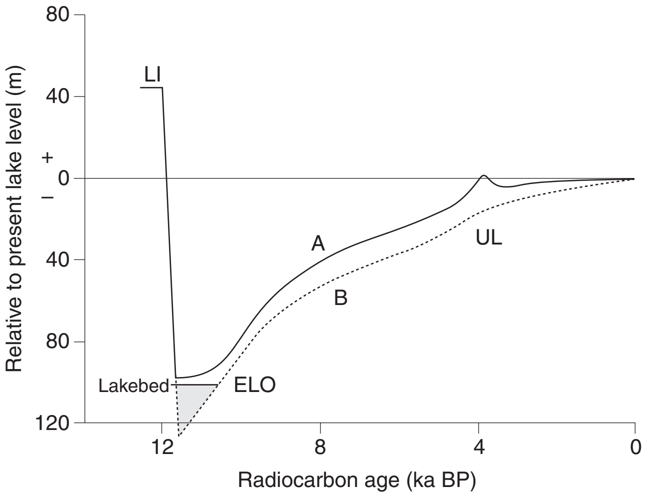

FIGURE 2. Relative lake level for the western end of Lake Ontario following the drainage of Lake Iroquois (LI). ELO: Early Lake Ontario, UL: increased drainage received from the Upper Lakes during the Nipissing event, A: Curve from Anderson and Lewis (1985), B: Curve from Sly and Prior (1984).

Niveau d'eau relatif de la partie ouest du lac Ontario près du lac Iroquois (LI). ELO : Early Lake Ontario, UL : Drainage accru en provenance des lacs durant l'évenement Nipissing, A : Courbe de Anderson et Lewis (1985), B : Courbe de Sly et Prior (1984).

and Lewis (1985). The main stage of Lake Iroquois was about 40 to 45 m above contemporary lake levels. At the west end of the basin, water levels during the falling stages of Lake Iroquois may have reached as much as 100 to 125 m below present day lake level (Sly and Prior, 1984; Anderson and Lewis, 1985). Rising water levels of early Lake Ontario between *ca.* 11 500 and 5000 ^{14}C BP are generally associated with greater isostatic rebound at the basin's eastern outlets (Anderson and Lewis, 1985). With the exception of the Nipissing Food phase (*ca.* 5000 to 4000 ^{14}C BP), Lake Ontario water level continued to rise to the present day elevation (Anderson and Lewis, 1985).

These post-glacial events will be examined further in the context of the Humber River basin, a sub-basin of the contemporary Lake Ontario basin. Observations of valley morphology using a DEM and of incision chronology using radiocarbon dates will be used to investigate valley evolution in the Humber River basin. Although an accurate knowledge of the processes and events which formed these valleys would require a more intense research design, observations made in this study may provide insight, and perhaps guide future research questions.

STUDY AREA

The present day Humber River basin, a sub-basin of the greater Lake Ontario basin, drains an area of about 900 km^2 at the northwest end of the lake. With headwaters beginning on the Oak Ridges Moraine, the Humber River and the East Humber River converge and flow south through incised valleys to their confluence (Fig. 3). These incised valleys generally follow a winding course, at times cut 30 to 50 m below the surrounding uplands. The valleys also appear to have a complex erosional history with many river terraces and valley widths ranging from 500 to 1 000 m. At the confluence, the main branch of the Humber River then continues to flow south through a narrow incised valley (width generally less than 200 m) before emptying into Lake Ontario.

Surficial geology within the basin is dominated by moraine sediments, glacial tills, and glacial lacustrine deposits left by the receding ice sheet (Sharpe *et al.* 1999). The younger surface tills (*e.g.* Halton Till) overlie older tills and sediments (*e.g.* Newmarket Till) which in turn overlie bedrock. The narrow incised valley of the lower Humber River is at times cut through the overburden, exposing the underlying Paleozoic shales (Chapman and Putnam, 1984).

As the incised valleys of the Humber River and East Humber River above the confluence exhibit complex erosional histories, they presumably possess the most information about their post-glacial evolution. Three field sites were selected along the East Humber River near Kleinburg, Ontario (Fig. 3), based on the occurrence of multiple terraces and abandoned channels. East Humber Valley 1 (EHV1) is located upstream of Kleinburg, East Humber Valley 2 (EHV2) is located at Kleinburg, and East Humber Valley 3 (EHV3) is located downstream of Kleinburg.

METHODOLOGY

In order to assess the evolution of river valleys in the Humber River basin, this study combines analysis of digital elevation models (DEM), topographic maps, surface geology maps, and field data. Surface geology data were obtained from the Geological Survey of Canada (Sharpe *et al.,* 2001).

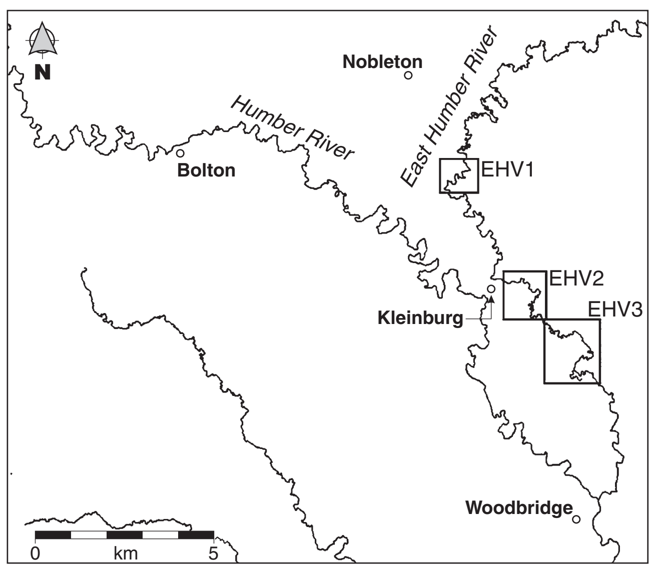

FIGURE 3. Location map of field sites on the East Humber River.

Carte de localisation des sites le long de la rivière East Humber.

Field work at all study sites included stratigraphic description, radiocarbon sampling, and topographic surveys. Field surveys included valley geometry and terrace elevations for reference to maps and other digital geospatial data. Aerial photography was used in the format of digital orthophotographs for interpretation of features and site characteristics.

Digital elevation models (DEM) represent the landscape using a grid of 10 by 10 m cells which are assigned a value for elevation above sea level in 1 m intervals. Initial investigation of the DEM allowed for qualitative assessment of valley characteristics and morphology. Distance measurements, slope analysis, valley delineation, and river terrace identification were then performed using the DEM, orthophotography, and field survey results. As a generalization of the landscape, the vertical scale of the DEM was not adequate to represent floodplain morphology (*e.g.* terraces) within a few metres of the valley floor. For this reason field surveys and aerial photography were necessary to verify and supplement the DEM information. In addition to mapping of the valleys, the DEM was used in combination with drainage networks to collect information such as drainage areas and measurements of valley features (*e.g.* valley meanders).

Measurements of valley loop diameters was performed by manually fitting circles to the features. The circles were fit to the base of slope along the valley wall, which was identified using a slope analysis within the DEM. The diameter of curvature results were then statistically plotted against contemporary drainage area. To smooth out some variation in the data points, the valley loop data was also tested based on clusters of loop features which were given a common drainage area.

Terrace features were mapped and longitudinal profiles developed using the DEM, orthophotography, and field surveys. Following terrace identification, valley cross-sections were then extracted from the DEM and, in some cases, verified with a field survey. If terrace features were not flat, an average surface elevation was extracted from the DEM. The distances along a valley centre line were then mapped and extracted using the orthophotography and DEM.

Radiocarbon samples were collected from each field site to investigate valley incision chronology. Methods and interpretations regarding radiocarbon samples are summarized in Table I. Generally organic matter was extracted from alluvial deposits and chronological interpretations could then be based on the sample's location relative to the geomorphic features of the site. Unless otherwise noted all dates are given in uncalibrated radiocarbon ages and have not been used to calculate absolute rates.

RESULTS

DIGITAL ELEVATION MODELS AND VALLEY LOOPS

Initial investigation of the Humber River basin DEM revealed a remarkable set of valley forms. The valley morphology along some sections of the Humber River and East Humber River clearly exhibits forms and artifacts of a former river environment which was much larger than the contemporary river system. Such observations have been made in many other environments, and are often attributed to wetter paleoclimates or melt-water during deglaciation. However, what makes these forms rather distinct is their tortuous meandering and the unique set of conditions which must have been present in order produce this morphology. The primary evidence for larger paleorivers is the scale of meandering exhibited in the valley landforms; however, poorly preserved paleochannel features observed from aerial photography exhibit widths of 50 to 80 m (approximately 2.5 to 4 times contemporary channel widths).

An image of the DEM (Fig. 4) illustrates the morphology of the East Humber and Humber river valleys. From these relic river forms, two distinct sets of morphology can be recognized in the drainage basin: wide valleys with complex erosional forms in the middle Humber and narrow incised valleys in the lower Humber reaches. Focusing on the morphology of the middle Humber, the first apparent form is the meandering of the valley (Fig. 4A). Although the valley is incised into the glacial stratigraphy, distinct valley meandering is recorded in the landscape. Another apparent form is the large loop features

TABLE I

Methods and interpretation of radiocarbon samples

Site/Sample	Study focus	Sampling location and procedure	Interpretation of sample history
EHV2 KB39.1	Holocene valley evolution	Abandoned Channel – From base of organic matter accumulation. Organic matter extracted using metal cylinder core.	Represents organic matter accumulation immediately following channel abandonment.
EHV2 KB39.2	Holocene valley evolution	Intermediate Terrace – From alluvial deposits above coarse paleobed material. Organic matter extracted using test pit and soil auger.	Represents vegetative matter deposited on an active point-bar during the time when the river channel was active at the elevation of the terrace.
EHV1 KR1.1	Recent channel incision	Low Terrace – From point-bar deposits above coarse paleobed material. Wood fragment extracted from test pit.	Represents woody organic matter deposited on the point-bar and followed by further lateral migration and then channel abandonment.
EHV3 KT10.1	Recent channel incision	Low Terrace – From point-bar deposit along exposed cut-bank. Organic matter extracted from behind exposed surface with trowel.	Represents vegetative matter accumulation on the point-bar as the former channel migrated laterally.

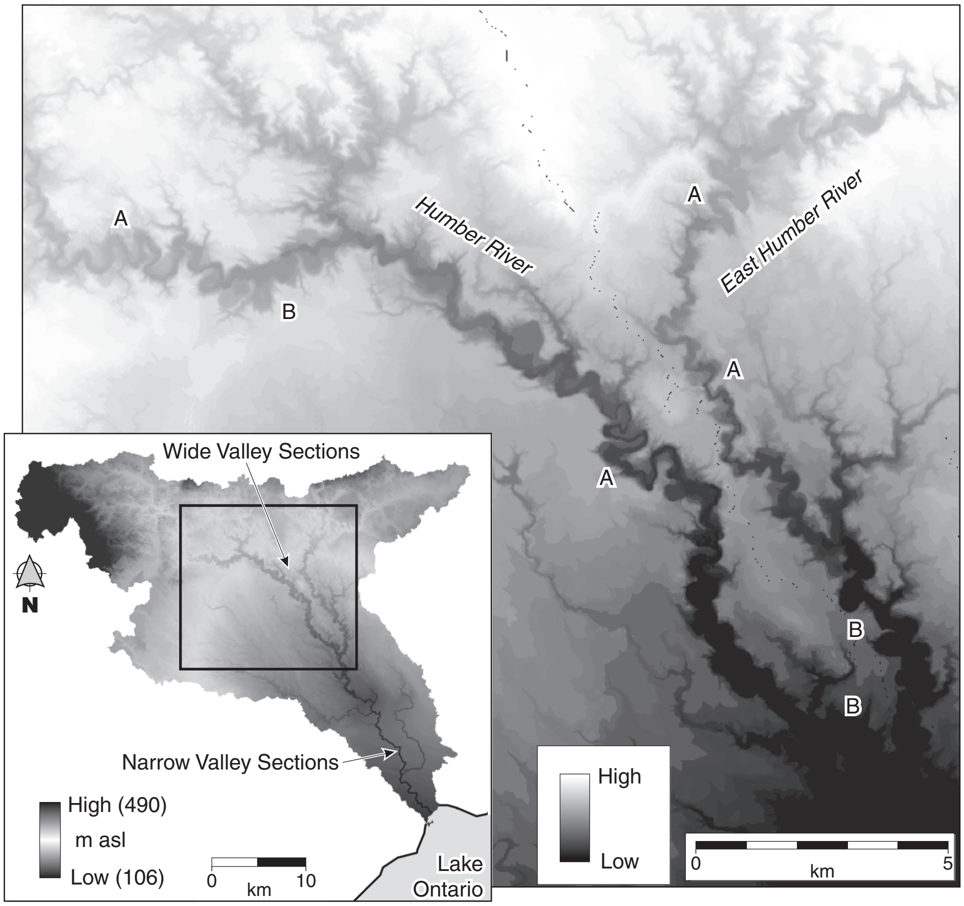

FIGURE 4. DEM of the Humber River basin showing planform morphology of incised river valleys. The landscape is represented in 10 m x 10 m pixels, which are assigned an elevation above sea level in 1 m intervals. A: Examples of valley meandering, B: Examples of valley loop features.

Modèle numérique d'élévation du bassin de la rivière Humber montrant la morphologie en plan des rivières incisées. Le paysage est représenté avec des pixels de 10 m x 10 m, avec des valeurs assignées d'élévation au-dessus du niveau moyen des mers à des intervalles de 1 m. A : Exemples de méandres, B : Exemples des caractéristiques des boucles de méandre.

preserved in the geometry of the valley walls (Fig. 4B). These valley loops appear to be large meander loops which were cutoff during the process of incision. As a result, some valley reaches appear relatively straight, yet have loops preserved on either side of the valley.

These forms are not analogous to broad glacial outwash plains with braided channels or to large glacial spillways common in the Canadian Prairies, which are commonly associated with glacial meltwater. The primary difference is the tortuous meandering forms. As well, the scale of the valley meandering features appears to generally increase as one progresses down valley. Given the well known relationships between drainage area, discharge, and meander scale (Schumm, 1967), this suggests that there might be some distinguishable relationship between the scale of the features and the location of the features within the drainage basin. In fact, a plot of the diameter of curvature of the most well preserved valley loops against the contemporary drainage-basin area does show a statistically significant correlation (Fig. 5 and Table II). A plot of the data from each branch which includes averaging some loops into clusters (with a common drainage area) provides a higher level of correlation and still maintains statistical significance. As a gap in the Humber River data was noted (Fig. 5A), the linear regression tests were divided into upper and lower data subsets for the main branch (Table II).

The paleodischarges associated with the scale of these forms are clearly much larger than the discharges of the contemporary regime. Although there are extreme uncertainties in applying empirically derived equations to specific cases using vague estimates of former channel properties, paleodischarge estimates using meander wavelength can still offer some perspective. Applying a stereotype for the relationship between valley meander wavelength and formative discharge, given by Dury (1985), provides a paleodischarge which is approximately ten times larger than the present day mean annual flood of the Humber River gauged near Bolton (Fig. 6). The existence of this specific valley morphology in the Humber River basin suggests a unique set of circumstances during deglaciation and the early Holocene. In order to investigate these environmental conditions further, vertical incision and terrace patterns were also examined.

TERRACE PATTERNS AND RIVER INCISION

Generally, river incision is a process whereby channel erosion, particularly at the bed, results in the removal of underlying sediment to areas downstream, and ultimately beyond the outlet. By this process, rivers may tend to lower their relative elevation within the surrounding landscape. River terraces represent former floodplain levels which have since been abandoned by processes of incision.

Terrace elevations on the East Humber River have been evaluated for this study using the DEM and field surveys (Fig. 7). This work complements earlier work done by Roberts

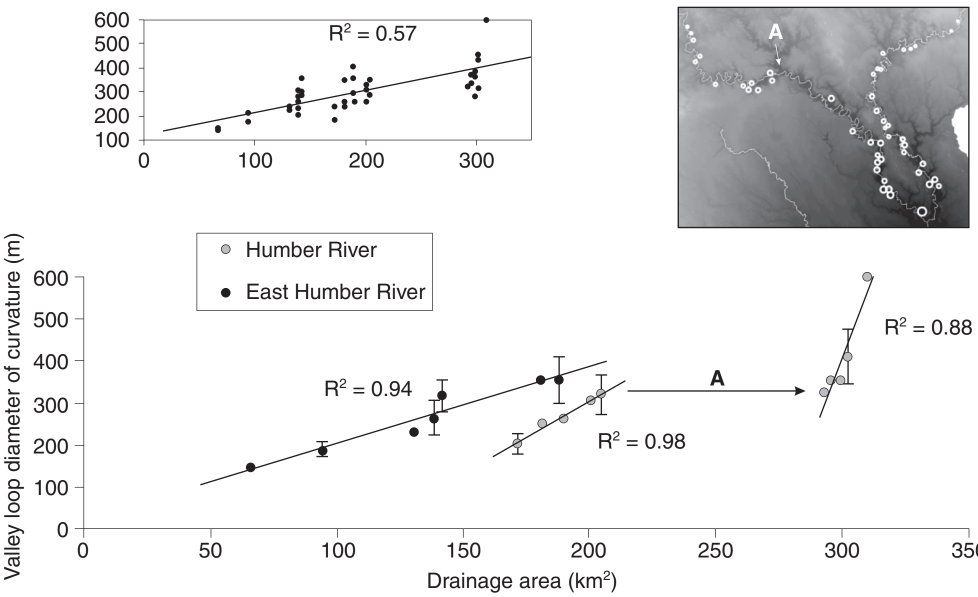

FIGURE 5. Positive correlation between the size of valley loop features and their location in the basin. R-squared values from simple linear regression show good correlation within subsets of the data and the slopes of the regression lines are statistically significant. A: Contemporary drainage area which contributes to displacement of Humber River data.

Corrélation positive entre la taille des boucles de méandres et leur localisation dans le bassin. Les R^2 de la régression linéaire simple montrent une bonne corrélation entre la subdivision des données et les pentes des droites de régression sont statistiquement significatives. A : Aire de drainage contemporaine contribuant au déplacement des données de la rivière Humber.

(1966). The highest terraces observed on the East Humber River (Fig. 7) are rare and at elevations between 16 and 21 m above the contemporary floodplain. Given the elevation of these surfaces above the contemporary floodplain and their relative age, the reduced preservation of these features allows for little further interpretation in this study. However, it is likely that these features were formed very soon after deglaciation.

The intermediate level terraces observed on the East Humber river are well preserved and common throughout the valley. On average these terraces are 10 m above the contemporary floodplain. Further, the regularity observed in the elevation of these intermediate terraces above the contemporary floodplain suggests that they can generally be associated with basin-wide adjustments and may roughly represent a continuous relic floodplain level of a common age. The radiocarbon sample KB39.2 taken from an intermediate terrace at EHV2 suggests an age of 8850 ± 1170 ^{14}C BP (Table III). As this sample is thought to represent deposited organic matter on an active point-bar, this age approximates a time when the river channel was active at an intermediate elevation above the contemporary floodplain. Figure 8 is a schematic diagram of the intermediate terraces at EHV2 and associated radiocarbon dates.

In addition to the error given in the radiocarbon date, there are other possible circumstances which should be considered in relation to this date. Although the organic sample was suspended in the sediments, it must be assumed that the burial of the sample coincides with the death of the organic material. If the death occurred much before burial, then the surface would appear older than it is. Also, it is assumed that the burial of the material was soon followed by channel and floodplain abandonment. If the surface was active long after the burial of the material, then the surface will have been active more recently than inferred. Generally, this radiocarbon date identifies an approximate time when the surface was active, and the "lifetime" of the surface may have begun earlier and ended after this date. Further boundaries on this date can be suggested by examining lower terrace elevations.

The low terraces shown in Figure 7 are generally less than 2 m from the contemporary floodplain, with one terrace documented at 5 m. Terraces at this level are close to the contemporary floodplain level and evaluation based on elevation is crude. As such, it is expected that not all low terraces have been documented within this study.

The radiocarbon sample KB39.1 taken from an abandoned channel on a low terrace at EHV2 suggests that the age of the channel is 5340 ± 80 ^{14}C BP (Table III). The most significant implication of this date is that it suggests there has been very little incision over the last six thousand years. As the sample

TABLE II

Linear regression statistics for valley loops vs. drainage area

Valley loop data Diameter of curvature (m) vs. drainage area (km²)	R^2 value for regression line	Slope of regression line	P-Value for slope of regression line
All data from basin	0.57	0.92	< 0.0001
East Humber with clusters averaged	0.94	1.80	0.0003
Humber upstream of 'A' with clusters averaged	0.98	3.43	0.0015
Humber downstream of 'A' with clusters averaged	0.88	15.7	0.0189

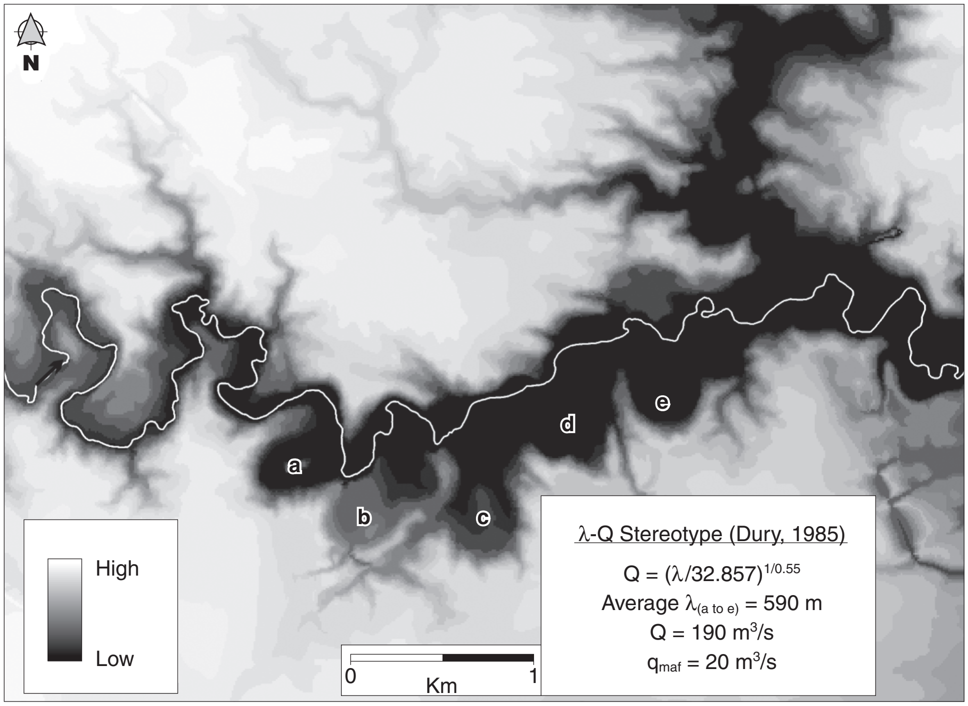

FIGURE 6. DEM of the Humber River valley at Bolton showing valley meandering and valley loop features (a to e). Dury's (1985) stereotype for the relationship between meander wavelength (λ) and discharge estimates a paleo-discharge (Q) about 10 times greater than the contemporary mean-annual-flood discharge (q_{maf}).

Modèle numérique d'élévation de la vallée de la rivière Humber à Bolton montrant les boucles de méandres (a à e). La relation empirique établie par Dury (1985) entre la longueur d'onde des méandres (l) et les débits estimés (Q) indique un débit 10 fois plus grand que le débit annuel moyen actuel (q_{maf}).

was taken from the base of the organic matter accumulation, it is thought to represent the approximate time of channel abandonment. While the elevation of the surface was likely established much before the channel was abandoned, the chronology of river incision at this location is limited by the age of the intermediate terrace surface (Fig. 7).

A schematic plot of floodplain level at EHV2 following regional deglaciation shows the general trends of incision (Fig. 9). Interpretation of terrace patterns and associated radiocarbon dates suggest that most incision occurred following deglaciation and during the early Holocene. Further, late Holocene incision has been insignificant in comparison. However, some incision has occurred in the late Holocene, as shown by the existence of low terraces and visible erosion within the contemporary channel.

RECENT INCISION

Evidence of recent incision is apparent in cutbank exposures at many sites on the East Humber River and Humber River. Commonly, lateral channel erosion exposes sections of

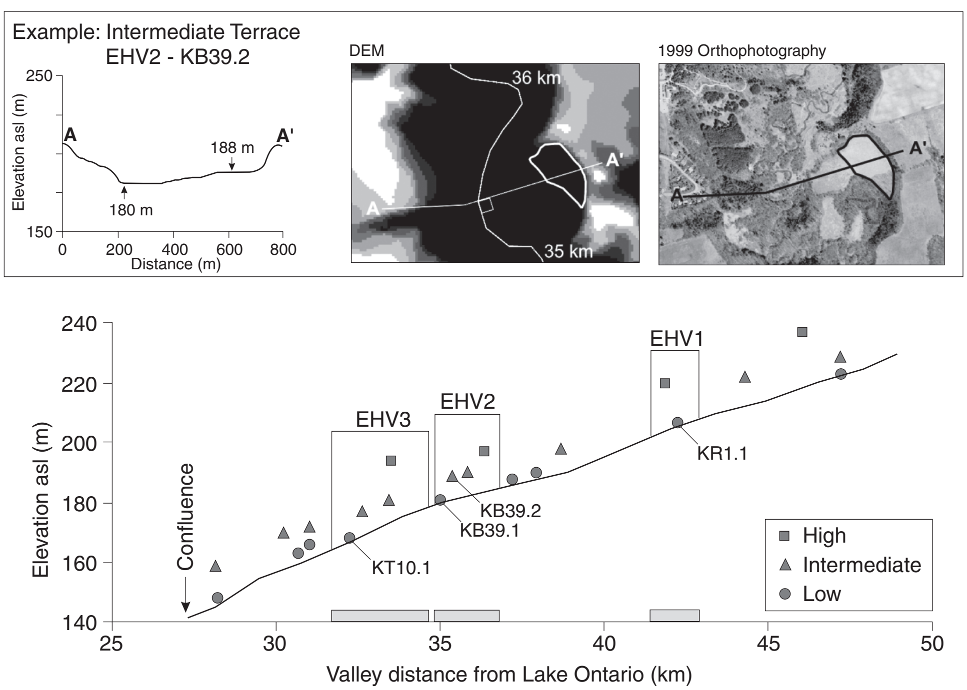

FIGURE 7. Profile of the East Humber River showing the location of terraces, study sites, and radiocarbon sampling locations. A general threefold terrace sequence is apparent. Terrace elevations were determined using field survey data, DEM, and orthophotography.

Profil de la rivière East Humber montrant la localisation des terrasses, des sites d'étude et la position des datations au ^{14}C. Une séquence de terrasses est manifeste. L'élévation des terrasses est déterminée avec les données de terrain, le MNE et l'orthophotographie.

TABLE III

Radiocarbon ages of the East Humber River valley

Site/Sample	Elevation asl (m)	(m) above paleo-bed	(m) above river-bed	Radiocarbon age (Lab number)*	Geomorphic position and sample type
EHV2 KB39.1	177.5	0.1	0.8	5340 ± 80 (TO-11924)	Abandoned channel, organics above paleo-bed
EHV2 KB39.2	188.9	0.5	12.2	8850 ± 1170 (TO-11981)**	Terrace alluvial deposits, organics in sediment
EHV1 KR1.1	204.9	0.5	2.2	690 ± 60 (TO-11925)	Terrace alluvial deposits, wood fragment in sediment
EHV3 KT10.1	166.6	0.3	2.1	Modern (60 ± 50) (TO-11996)	Alluvial point-bar deposits, organic layer in sand strata

* Dating performed using Atomic Mass Spectroscopy (AMS) by IsoTrace Laboratories at University of Toronto, Ontario.

** Larger error due to lower carbon content in sample.

floodplain stratigraphy which suggest that the channels are locally incising into the glacial material below. These exposures are generally characterized by a resistant glacial sequence, overlain by a package of alluvial sediments with coarse gravel and cobble at the base. Two of these sections will be described from sites along the East Humber River: EHV1 and EHV3.

Although lateral channel migration at EHV1 is limited by its confinement between elevated terrace surfaces, much of the reach at this site is characterized by exposures of massive glaciolacustrine clay. The abandoned channel at this site is on a raised terrace about 1.5 m above the contemporary floodplain. A cut-bank exposure of the terrace stratigraphy shows the alluvial package of sediments, the coarse cobble and gravel base, and the underlying glaciolacustrine clay (Fig. 10). This clay exposure above the baseflow water-surface extends down to the contemporary channel bed, and perhaps lower.

Following channel abandonment at this site, it appears that incision has occurred. The radiocarbon sample KR1.1 taken from the alluvial point bar deposits of the abandoned channel suggests an age of 690 ± 60 ^{14}C BP (Table III). In order to obtain a date which closely approximates the time just before the channel was abandoned, the radiocarbon sample was taken from point-bar sediments adjacent to the abandoned channel. It is still possible, however, that the channel was active for some time at a stable position following the death and burial of the organic material, before channel abandonment occurred. While this date does not provide a precise time of abandonment or rate of incision, it does suggest that this local incision has occurred roughly within the last thousand years and possibly more recently.

A second example of recent incision on the East Humber River is found at the EHV3 field site. While this example again shows a stereotypical terrace stratigraphy, incision and terrace formation appears to be the result of significant lateral channel migration rather than channel abandonment. A cut-bank exposure of this terrace stratigraphy shows well preserved sandy point-bar deposits with a coarse gravel at the base (Fig. 11). This alluvial package rests over a dense glacial till with a sandy-silt matrix and sparse gravel to cobble size clasts. Again, this glacial material extends from above the baseflow water-surface down to the contemporary channel bed, and perhaps lower.

The suggested meander migration pattern is evident based on the channel geometry and recent channel shifting (Fig. 11);

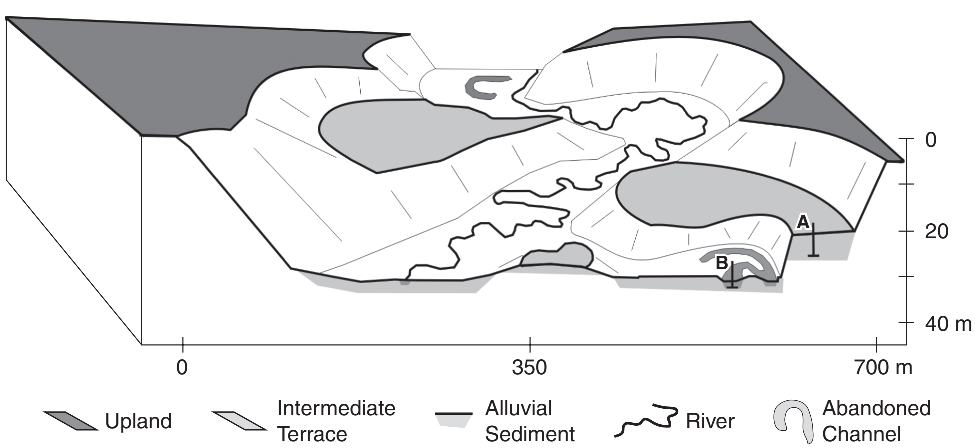

FIGURE 8. A three-dimensional diagram of the East Humber River valley at Kleinburg, illustrating the depth of valley incision and the elevation of intermediate terraces. A: KB39.2: 8850 ± 1170 ^{14}C BP, B: KB39.1: 5340 ± 80 ^{14}C BP.

Diagramme tridimensionnel de la vallée de la rivière East Humber à Kleinburg illustrant la profondeur de l'incision de la vallée et l'élévation des terrasses intermédiaires. A : KB39.2 : 8850 ± 1170 ^{14}C BP, B: KB39.1: 5340 ± 80 ^{14}C BP.

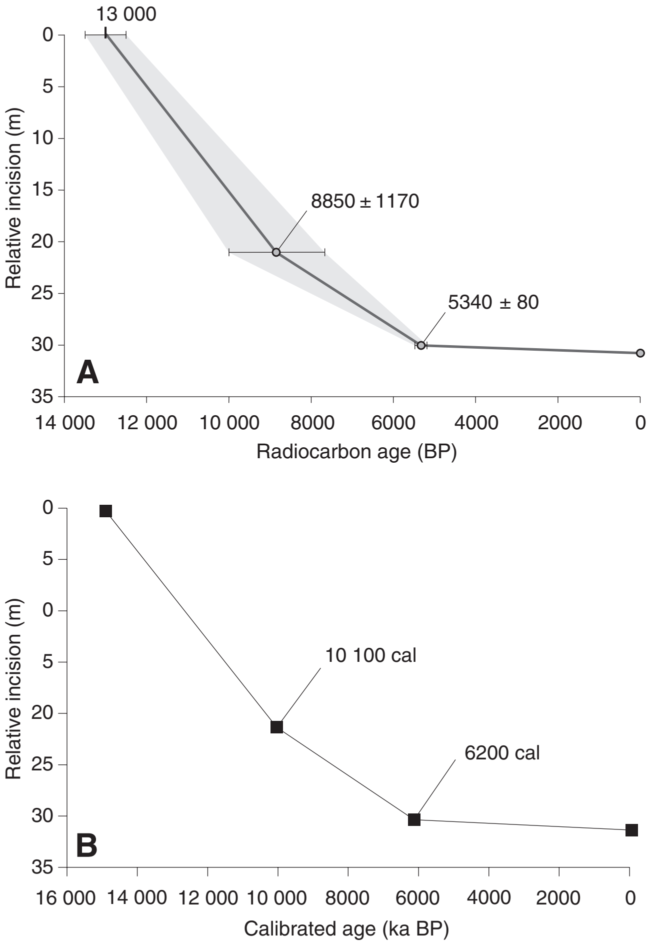

FIGURE 9. Plot of relative incision at Kleinburg since deglaciation (showing rapid incision initially followed by slow incision in the late Holocene). A: The shaded zone provides an envelope which links the dating of deglaciation (13 000 ^{14}C BP) from previous research (Terasmae, 1980; Chapman and Putnam, 1984) with radiocarbon date error bars from this study. B: Plot of calibrated ages provides the same pattern of incision.

Diagramme de l'incision relative estimée au site de Kleinburg depuis la déglaciation (on observe une incision initiale rapide suivie d'une diminution du taux d'incision plus lent au cours de l'Holocène). A : La zone ombragée associe l'âge de la déglaciation (13 000 ^{14}C BP) des études précédentes (Terasmae, 1980; Chapman et Putnam, 1984) aux erreurs des dates au radiocarbone de cette étude. B : Le diagramme des âges étalonnés montre le même patron d'incision.

as well, the pattern of point-bar shifting apparent in the stratigraphy suggests that migration was in a northward direction. As the evolving meander bends shifted laterally, vertical incision was also occurring. This simultaneous lateral and downward shifting has ultimately resulted in a raised alluvial package and exposure of the underlying glaciogenic material. The radiocarbon sample KT10.1 taken from an organic layer within the point-bar deposits suggests an age of 60 ± 50 ^{14}C BP (Table III). Although this age appears much too recent to allow for the observed amount of migration and incision, problems associated with calibration between radiocarbon years and calendar years allows for the association of multiple calendar dates with a single radiocarbon date. Aside from any error in the radiocarbon date itself, it is still possible that the calendar age of this sample is over 200 years old. What this suggests again is that this observed incision is relatively recent.

DISCUSSION

Valley evolution in the Humber River basin is generally characterized by initially rapid incision into the post-glacial landscape, with much less incision through the late Holocene (Fig. 9). Based on the character of valley evolution investigated in this study, and the established interpretation of post-glacial events, some general observations can be made which may account for the valley geomorphology observed today.

Interpretation of valley evolution in the Humber River basin can be achieved by looking at the rough chronological correlation between post-glacial events and inferred fluvial processes. Figure 12 illustrates a schematic representation of the postglacial incision in the Humber River basin identified in this study, and the associated deglaciation events and dates presented in the literature. Although there is still some uncertainty in the chronology of the events presented, the scale of the relationships illustrated here may still allow for some acceptable observations.

River valleys within the contemporary Humber River basin likely did not exist prior to the last glaciation; thus, the key event to begin this account is the formation of the Oak Ridges interlobate moraine between 15 000 and 13 000 ^{14}C BP. As the Lake Ontario lobe of the ice sheet retreated eastward, much of the landscape of the contemporary Humber River basin would have been uncovered. Given the general scale and pattern of postglacial rebound, this area was still likely characterized by a topographic high at the Oak Ridges Moraine. As well, surficial geology was characterized by a complex stratigraphy of basal till, glaciolacustrine clays, and glaciofluvial deposits on the south slope. As this surface exposure persisted, processes of fluvial erosion and stream channel initiation would have begun to carve up the landscape. Based on the observations of valley morphology from the DEM, the channel pattern appears to have been initially characterized by sinuous meandering into the exposed glaciogenic deposits.

During the establishment and existence of Lake Iroquois in the Lake Ontario basin, ice retreat north of the Oak Ridges Moraine was also occurring and was associated with the development and existence of glacial Lakes Schomberg and Algonquin. These proglacial lakes are generally associated with the Huron basin; however, it is thought that lake levels submerged many areas north of the Oak Ridges Moraine and surrounding present day Lake Simcoe (Fig. 1). Despite considerations for isostatic depression by the Laurentide Ice Sheet and patterns of glacial rebound, raised water levels in this area would generally have been at a higher elevation compared to water levels in the Lake Ontario basin. This is supported by evidence of drainage from Lake Algonquin to the Ontario basin (Chapman and Putnam, 1984). Based on this fact, infiltration and groundwater flux patterns would have been characterized by flow through the complex stratigraphy to the south, some of it likely associated with Oak Ridges Moraine

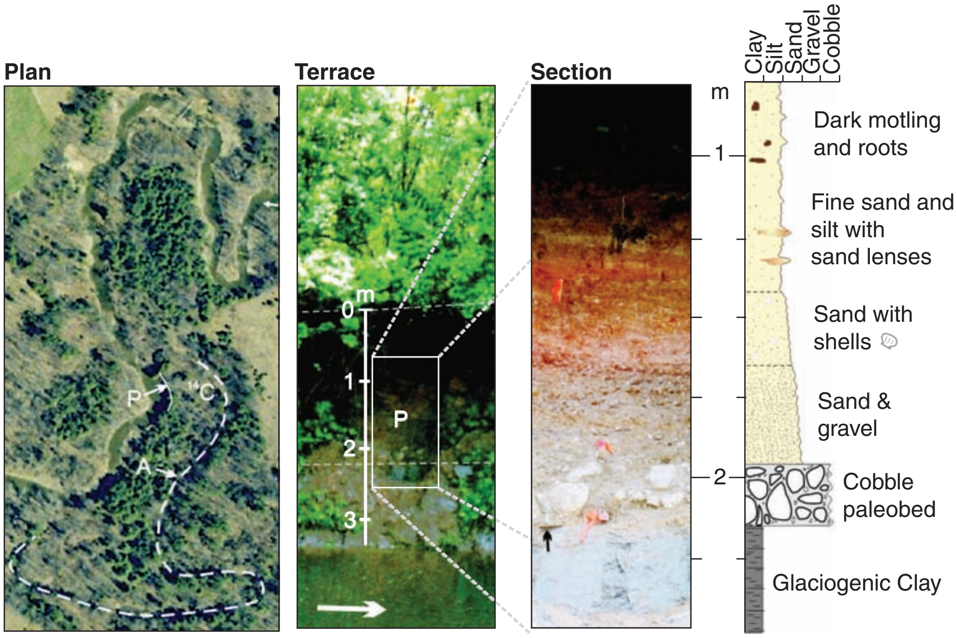

FIGURE 10. Exposed section at EHV1 showing a package of alluvial sediments overlying non-alluvial material. This channel reach appears to be incising and has exposed a dense grey clay. P: Position of photograph, ^{14}C: Radiocarbon date (KR1.1: 690 ± 60 ^{14}C BP), A: Abandoned channel.

Section exposée au site EHV1 montrant des alluvions au-dessus d'un matériel d'origine non-alluvial. Cette section du chenal semble continuer à s'inciser et expose une couche d'argile grise et dense. P : Localisation de la photographie, ^{14}C : Date au radiocarbone (KR1.1 : 690 ± 60 ^{14}C BP), A : Chenal abandonné.

sediments. This pattern of hydraulic head would have interesting implications for baseflow and stream-flow patterns on the south slopes of the moraine.

The scale of meandering forms measured from the DEM (Fig. 6) suggest that paleochannels were much larger during initial incision. If the ancestral rivers in the Humber River basin were indeed much larger than today, this would require greater sources of water. Given the distribution of surficial accumulations of moraine sediments, it is also possible that northern ice was positioned at the moraine for some period of time following the withdrawal of the Ontario basin lobe to the south. Thus, initial fluvial incision south of the moraine could have been driven by melt-water directly from the melting edges of the northern ice; however, it is unclear if the timing and formative history of the moraine support this suggestion. It is also unclear if this can explain the character and timing of valley evolution.

Further melting and ice retreat north of the moraine generally resulted in melt-water collection by proglacial lakes, but there is little topographic or sedimentary evidence that overspill to the south was a significant process. There is some minor evidence of overspill in the surficial sediments just northeast of Nobleton (see Fig. 3 for location) and it has been speculated that some overspill at the moraine may have occurred near Palgrave (Eschman and Karrow, 1985); however, if overspill was a dominant factor in valley formation on the south slope, then headwater valleys should extend over the moraine.

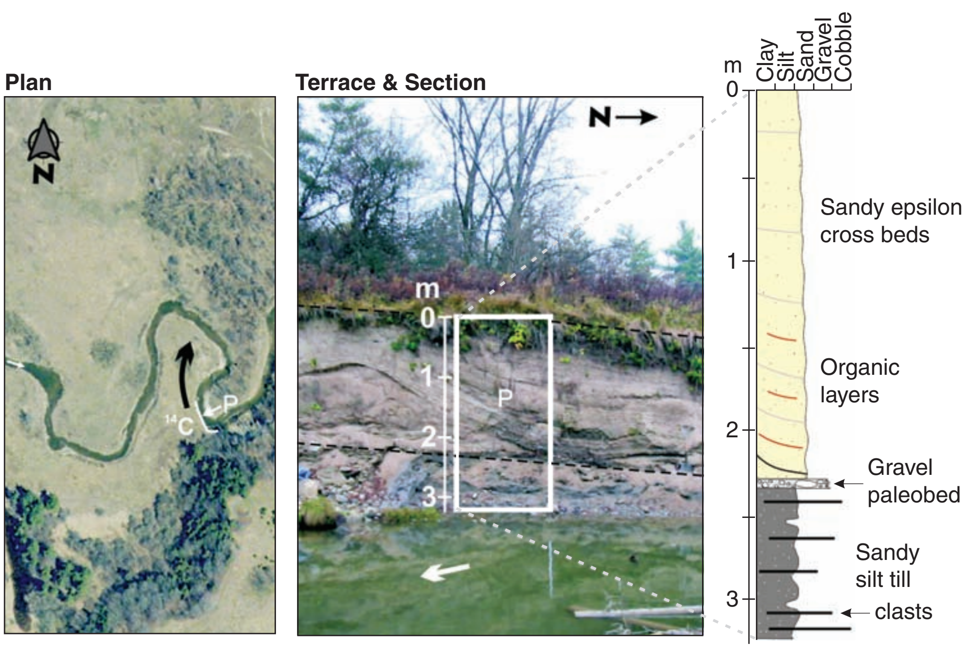

FIGURE 11. Exposed section at EHV3 showing alluvial point-bar deposits overlying a glaciogenic till deposit. Epsilon cross-bedding suggests channel migration was generally in a northward direction. The contemporary channel appears to be incising. P: Position of photograph, ^{14}C: Radiocarbon date (KT10.1: 60 ± 50 ^{14}C BP).

Section exposée au site EHV3 montrant les dépôts alluvionnaires reposant sur un dépôt d'origine glaciaire. Le chenal contemporain semble continuer à s'inciser. P : Localisation de la photographie, ^{14}C: Date au radiocarbone (KT10.1: 60 ± 50 ^{14}C BP).

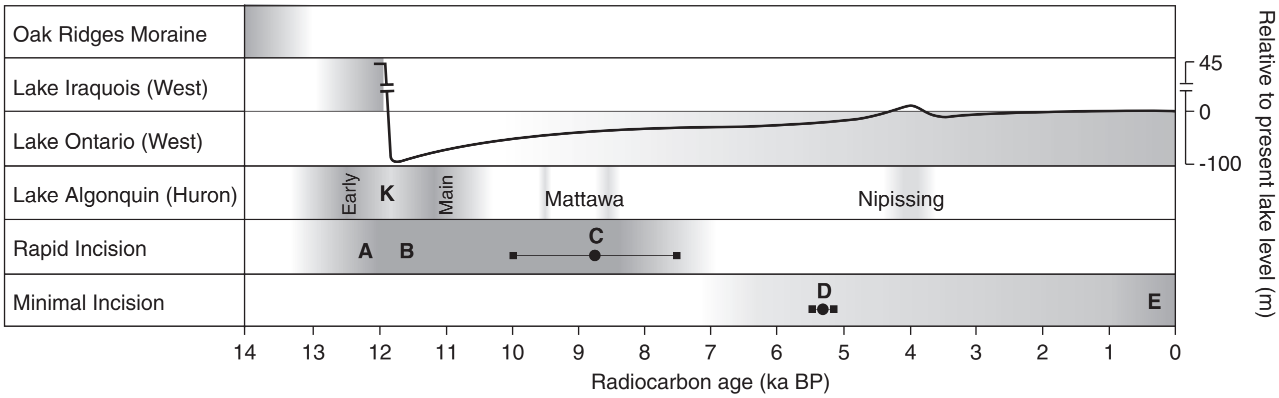

FIGURE 12. Chronological correlation of deglaciation events and river incision associated with the Humber River basin. A: Early fluvial incision due to melt-water with outlet temporarily associated with Lake Iroquois. B: Continued fluvial incision with possible readjustments due to the drop in base-level. C: Radiocarbon date of intermediate terrace at EHV2 (KB39.2) associated with 65% of vertical valley incision. D: Radiocarbon date of abandoned channel at EHV2 within one metre of the contemporary floodplain elevation. E: Some reactivation of incision, presumably associated with human settlement and development. K: Partial lowering of Lake Algonquin associated with drainage at Kirkfield. Deglacial chronology estimated from various sources (Karrow *et al.* 1961; Duckworth, 1979; Terasmae, 1980; Chapman and Putnam, 1984; Sly and Prior, 1984; Anderson and Lewis, 1985; Chapman, 1985; Eschman and Karrow, 1985; Muller and Prest, 1985; Yu *et al.* 1997; Yu and Wright, 2001).

Corrélation chronologique des événements de déglaciation et d'incision fluviale pour le bassin de la rivière Humber. A : Incision fluviale initiale associée aux eaux de fonte provenant temporairement du lac Iroquois. B : Poursuite de l'incision fluviale par des réajustements associés à la baisse du niveau de base. C : Datation au radiocarbone de la terrasse intermédiaire au site EHV2 (KB39.2) associée à 65% de l'incision de la vallée. D : Datation au radiocarbone d'un chenal abandonné au site EHV2 dans le premier mètre de la plaine inondable contemporaine. E : Réactivation de l'incision fluviale, probablement associée aux activités humaines. K : Diminution partielle du niveau du lac Algonquin associée au drainage à Kirkfield. La chronologie de déglaciation est fondée sur plusieurs sources (Karrow et al.*, 1961; Duckworth, 1979; Terasmae, 1980; Chapman et Putnam, 1984; Sly et Prior, 1984; Anderson et Lewis, 1985; Chapman, 1985; Eschman et Karrow, 1985; Muller et Prest 1985; Yu* et al.*, 1997; Yu et Wright, 2001).*

Overspill channels do not appear to be the dominant source of melt-water controlling valley evolution. Further, the direct contribution of significant melt-water to the drainage systems is not supported by the increasing size of valley features downstream. The melting front of a glacier or even a proglacial lake would be expected to deliver water independent of drainage area.

Instead, the increasing size of valley loops with increasing drainage area (Fig. 5) suggests that melt-water may have also indirectly supplied water to the Humber River basin by way of atmospheric or hydrogeologic sources. It seems logical that large accumulations of impounded water in the region would have moistened the atmosphere and induced significant groundwater flow through conductive sediments. While deeper hydrostratigraphy would have been involved, some of this groundwater flow would be associated with the Oak Ridges Moraine sediments. Moraine sediments are also associated with the in-filling of large sub-glacially formed channels (*i.e.* tunnel valleys), and moraine sediments have been documented at depths of 150 m, where the base may be lower than 130 m above sea level (Barnett *et al.* 1998). Referring to Figure 13, both main branches with the unique valley morphology originate from areas with significant moraine deposition. As well, the area of contemporary drainage between the two primary headwaters is an area where moraine deposition was not as significant. Consequently, this area also may not have contributed water as effectively during initial postglacial incision, as suggested in Figure 5. Along the Humber River valley, there are two groups of valley loop data separated by a sudden increase in drainage area which seems to leave the data disjointed (Fig. 5A). This pattern suggests that the contemporary drainage area, which contributes to this jump in drainage area, was a much less effective source of water during the formation of the these valley features.

Moraine sediments tend to consist of coarser material than the till and lacustrine deposits, and thus are generally more hydraulically conductive. Further, the fine texture and density of basal till and glaciolacustrine deposits impart lower hydraulic conductivities. Thus, the spatial association of headwater drainage, valley morphology, and moraine sediments suggests that a major source of water to the ancestral rivers may indeed have been supplied by pro-glacial lake levels to the north driving groundwater flux to the south slopes. Additional evidence of this relationship with the basin hydrostratigraphy is the contemporary drainage network surveys performed by Hinton *et al.* (1998) which show that most river baseflow in the basin is associated with moraine sediments.

Given the significant geomorphic effects of early river evolution compared to contemporary processes, it is logical to presume that paleorivers were more competent with regard to eroding and transporting sediment. Although river hydrology is an important factor, the character and supply of the sediment may also play a role in changing river competence through the course of river evolution. As much of the postglacial surface was characterized by a stratigraphic sequence of various glaciogenic materials, initial incision was likely associated with relatively young sediments, with potentially abundant silt and sand sized materials. In contrast, it is possible that late Holocene rivers have been eroding older, perhaps more resistant, deposits, and have suffered from a concentration of coarser

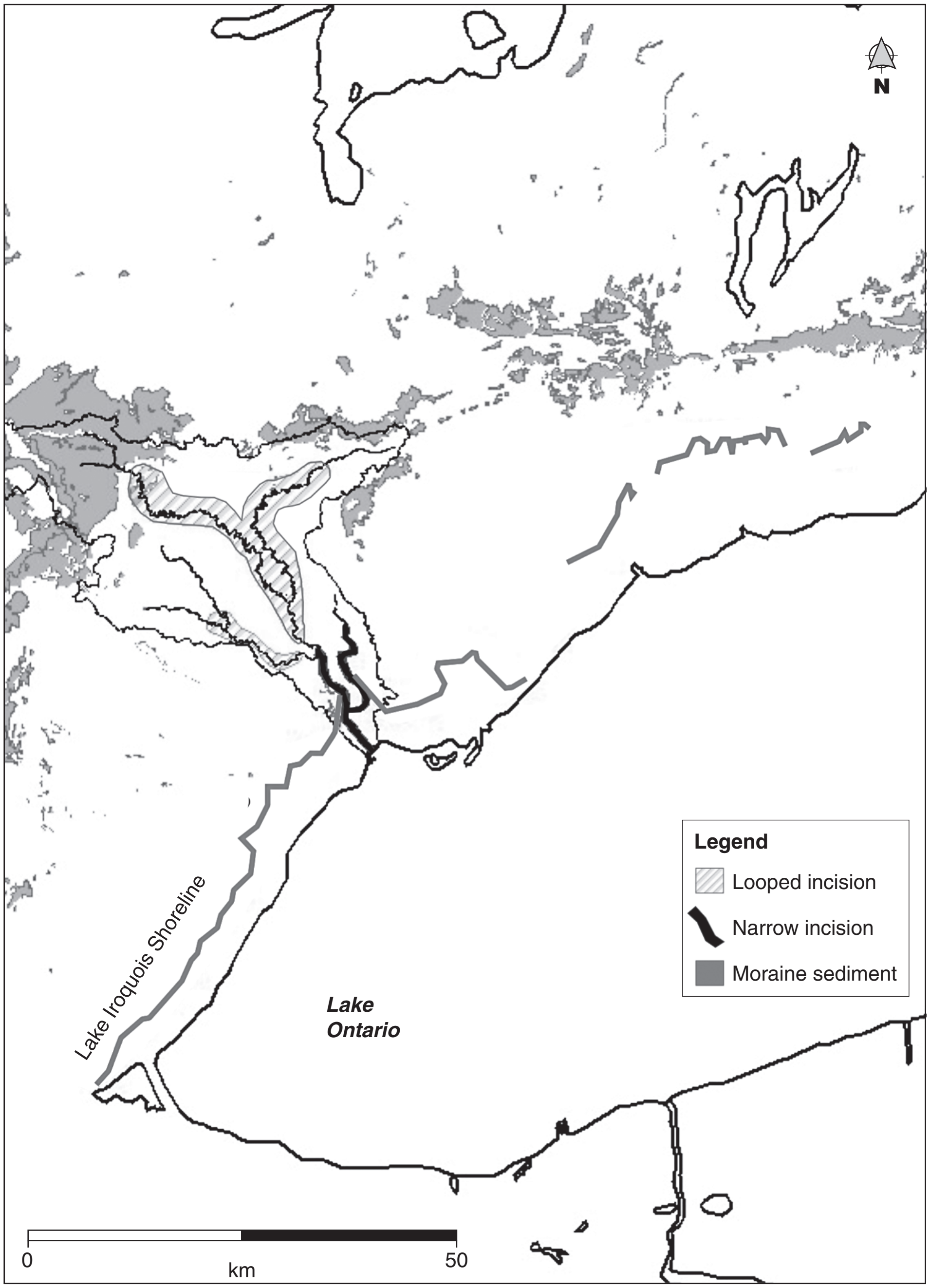

Figure 13. Map of Humber River basin showing extent of valley morphology in relation to surficial sediment distribution and raised shoreline. Shoreline and sediment distribution modified from Sharpe *et al.* (2001).

Carte de l'étendue de la morphologie des vallées en relation avec la distribution des dépôts de surface et du niveau du lac pour le bassin de la rivière Humber. Les lignes de rivage et la distribution des sédiments ont été modifiées d'après Sharpe et al. *(2001).*

material (*e.g.* till clasts) within the valley fill. This process is also suggested by the highly controlled and irregular meandering exhibited by the contemporary river channels.

Following the drainage of glacial Lake Iroquois after 12 000 ^{14}C BP, surfaces previously below the level of Lake Iroquois would have been exposed to the fluvial incision from the established drainage upstream. As levels of Early Lake Ontario were far below present day lake levels, this would have also included incision into the surfaces which are now lake bed. Sharpe *et al.* (1999) suggest that basin-wide readjustment may have been responsible for the common occurrence of the distinctive set of river terraces within some valleys. While this idea seems reasonable, there is some inconsistency when compared to the radiocarbon date suggested by the intermediate terrace at EHV2. Even the oldest age within the dating error indicates that the river did not abandon this terrace at the time Lake Iroquois was drained. In fact, the radiocarbon date suggests it was 1500 to 4000 ^{14}C BP later. However, it is possible that the response of the river channels upstream from the Lake Iroquois outlet was delayed.

Following a relatively rapid drop in base-level, incision can occur as a wave which migrates upstream (Knighton, 1998). Presumably, a drop in the base-level would cause incision near the outlet, but initially this would not effect local valley and

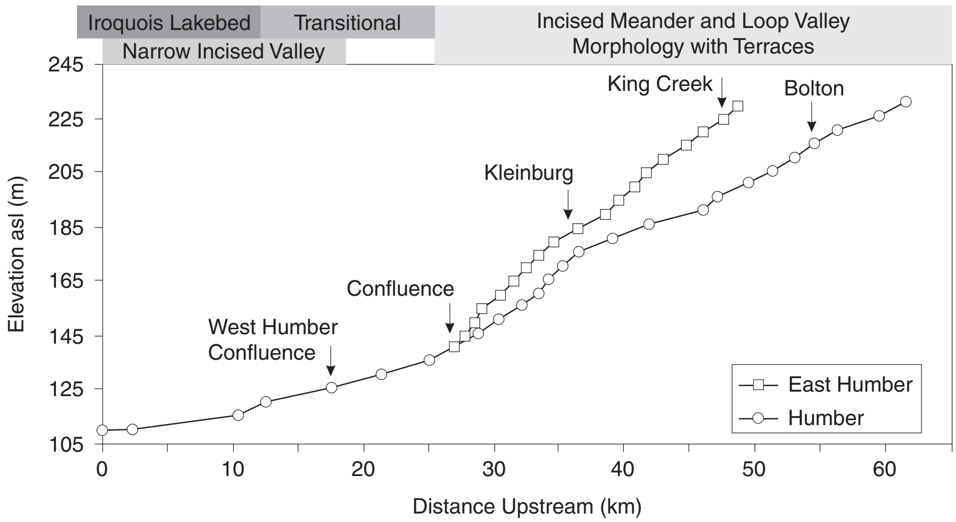

Figure 14. Valley profiles for the Humber River and East Humber River.

Profils de vallée des rivières Humber et East Humber.

channel slopes upstream. Although the contemporary river profiles do show an increase in slopes upstream of the confluence, terraces can be observed a great distance upstream, and thus this change in profile is likely a product of other basin controls (Fig. 14). Differences between the longitudinal profiles upstream of the confluence are likely controlled by differences in regional scale slopes (*i.e.* spatial character of regional topography immediately following glacial retreat). The longitudinal slopes of the terraces (Fig. 7) appear to closely follow the contemporary channel slopes. This suggests that differential uplift may not have influenced incision processes or that valley incision occurred over a very short period. It is possible that the rapid lowering of base-level due to drainage of Lake Iroquois had some effect on upstream incision, however, the timing and pattern of incision seem to be more complex.

The rising level of Lake Ontario through the Holocene would have reduced incision rates, particularly at reaches just above the outlet. Relatively little incision has occurred at EHV2 in the last 6000 ^{14}C BP (Fig. 9). Further, the end of Lake Algonquin roughly 10 500 ^{14}C BP would have reduced the amount of water received on the south slopes of the Oak Ridges Moraine. Consequently, most of the uncertainty regarding valley evolution lies in the period between 10 500 and 6000 ^{14}C BP. If incision was still active during this time, it is unclear what factors were the most important in driving it. If the majority of river incision occurred before the end of Lake Algonquin, this conflicts with the radiocarbon date taken at EHV2. Post-Algonquin incision could perhaps be associated with a warming of the Holocene climate following the Younger Dryas cold period (Yu and Wright, 2001) or with subsequent high lake stages in the Huron basin. During the Holocene, various high stages in the Lake Huron basin have been described and are thought to be associated with water from glacial Lake Agassiz (Teller, 1985; Buhay and Betcher, 1998). In particular, the Mattawa highstands occurred *ca.* 10 000 and 8000 ^{14}C BP, and the Nipissing Flood phase occurred *ca.* 5000 and 4000 ^{14}C BP (Eschman and Karrow, 1985; Lewis *et al.*, 1994). However, only the Mattawa highstands correlate with the age of the river terrace at EHV2, and evidence suggests that these lake levels did not significantly submerge areas immediately north of the Oak Ridges Moraine, presumably as a consequence of glacial rebound.

In addition to rising levels in the Lake Ontario basin over the middle Holocene, reduced incision may also have been aided by dryer climates. Evidence of this is shown by Yu *et al.* (1997) using shifts in oxygen isotopes at Crawford Lake just southwest of the Humber River basin. Yu *et al.* (1997) suggest that evidence at this lake indicates a dryer climate in the region between *ca.* 5000 and 2000 ^{14}C BP. Presumably climate following this period has become wetter, which may also be contributing to the slight increases in incision observed within the last 1000 ^{14}C BP.

Evidence discussed in this study (EHV1 and EHV3) suggests that there has been some reactivation of incision in the Humber River basin within the last one thousand years, and perhaps more recently. It is possible that this idea is supported by the work of Weninger and McAndrews (1989) on aggradation rates in the lower Humber River valley. Using sediment cores from two flood ponds, they found a significant increase in aggradation rates starting about 150 years ago. These rates far surpassed the measured late Holocene aggradation rates attributed to lake-level rise, prior to 150 years ago. These aggradation rates in the lower Humber River valley are generally considered a response to basin sediment supplies due to erosion from agricultural surfaces, but might also be due to increased incision upstream. Increased incision upstream is not surprising given the effects of deforestation and urbanization on decreases in evapotranspiration and infiltration, and increases in runoff.

While increased human settlement may be the driving factor behind recent incision, the effects of changing basin hydrology on local channel incision are relatively heterogeneous. Variations in local valley and channel slopes, valley confinement, and sediment characteristics will cause variations in the geomorphic response. For example, evidence of recent incision suggests more activity at the EHV1 and EHV3 field sites, with less apparent incision throughout the valley near EHV2.

CONCLUSION

In summary, observations of valley geometry, river terrace age, and patterns of incision in the Humber River basin, with respect to deglacial events and the early Holocene, indicate that initial incision was rapid and associated with proglacial lake levels and other processes related to both the direct and indirect effects of melt-water. In particular, the high water stages north of the Oak Ridges Moraine and outlet adjustments to the water levels of Lake Iroquois and early Lake Ontario, played a significant role in early valley evolution and river geomorphology. As paleoclimate reconstruction is less definitive, evidence of significant incision in the early Holocene can be attributed to a few possible factors such as an upstream sequence of basin-wide readjustment to a lowered base-level or the further influence of fluctuating lake levels in the Huron basin north of the moraine. While there is still uncertainty regarding incision during the early Holocene, very little incision has occurred during the late Holocene, with the exception of the recent channel incision associated with increased human settlement.

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